PATENT
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APPARATUS AND METHOD FOR PRODUCING TWO-SIDED PATTERNED WEBS IN REGISTRATION

Field

The invention relates generally to the continuous casting of material onto a web, and more specifically to the casting of articles having a high degree of registration between the patterns cast on opposite sides of the web.

Background

In the fabrication of many articles, from the printing of newspapers to the fabrication of sophisticated electronic and optical devices, it is necessary to apply some material that is at least temporarily in liquid form to opposite sides of a substrate. It is often the case that the material applied to the substrate is applied in a predetermined pattern; in the case of e.g. printing, ink is applied in the pattern of letters and pictures. It is common in such cases for there to be at least a minimum requirement for registration between the patterns on opposite sides of the substrate.

When the substrate is a discrete article such as a circuit board, the applicators of a pattern may usually rely on an edge to assist in achieving registration. But when the substrate is a web and it is not possible to rely on an edge of the substrate to periodically refer to in maintaining registration, the problem becomes a bit more difficult. Still, even in the case of webs, when the requirement for registration is not severe, e.g. a drift out of perfect registration of greater than 100 microns is tolerable, mechanical expedients are known for controlling the material application to that extent. The printing art is replete with devices capable of meeting such a standard.

However, in some products having patterns on opposite sides of a substrate, a much more accurate registration between the patterns is required. In such a case, if the web is not in

continuous motion, apparatuses are known that can apply material to such a standard. And if the web is in continuous motion, if it is tolerable, as in e.g. some types of flexible circuitry, to reset the patterning rolls to within 100 microns, or even 5 microns, of perfect registration once per revolution of the patterning rolls, the art still gives guidelines about how to proceed.

However, in e.g. optical articles such as brightness enhancement films, it is required for the patterns in the optically transparent polymer applied to opposite sides of a substrate to be out of registration by no more than a very small tolerance at any point in the tool rotation. Thus far, the art is silent about how to cast a patterned surface on opposite sides of a web that is in continuous motion so that the patterns are kept continuously, rather than intermittently, in registration within 100 microns.

Summary

One aspect of the present disclosure is directed to an apparatus for casting a patterned surface on both sides of a web while keeping a much finer registration between the patterns that has been possible in the past. The apparatus includes a first patterned roll and a second patterned roll for applying the patterns to the web. Also included is a means for rotating the first and second patterned rolls such that their patterns are transferred to opposite sides of the web while it is in continuous motion, and their patterns are maintained in continuous registration to within 100 microns. In another embodiment, a registration accuracy of within 50 microns can be accomplished, and in yet another embodiment, a registration accuracy of within 10 microns is possible.

Definitions

In the context of this disclosure, "registration," means the positioning of structures in a set location in relation to the edge of a web and to other structures on the opposite side of the same web.

In the context of this disclosure, "web" means a sheet of material having a fixed dimension in one direction and either a predetermined or indeterminate length in the orthogonal direction.

In the context of this disclosure, “continuous registration,” means that at all times during rotation of first and second patterned rolls the degree of registration between structures on the rolls is better than a specified limit.

In the context of this disclosure, "microreplicated" or "microreplication" means the production of a microstructured surface through a process where the structured surface features retain an individual feature fidelity during manufacture, from product-to-product, that varies no more than about 100 micrometers.

Brief Description Of The Drawing

In the several figures of the attached drawing, like parts bear like reference numerals, and:

FIG. 1 illustrates a perspective view of an example embodiment of a system including a system according to the present disclosure;

FIG. 2 illustrates a close-up view of a portion of the system of **FIG. 1** according to the present disclosure;

FIG. 3 illustrates another perspective view of the system of **FIG. 1** according to the present disclosure;

FIG. 4 illustrates a schematic view of a an example embodiment of a casting apparatus according to the present disclosure;

FIG. 5 illustrates a close-up view of a section of the casting apparatus of **FIG. 4** according to the present disclosure;

FIG. 6 illustrates a schematic view of an example embodiment of a roll mounting arrangement according to the present disclosure;

FIG. 7 illustrates a schematic view of an example embodiment of a mounting arrangement for a pair of patterned rolls according to the present disclosure;

FIG. 8 illustrates a schematic view of an example embodiment of a motor and roll arrangement according to the present disclosure;

FIG. 9 illustrates a schematic view of an example embodiment of a means for controlling the registration between rolls according to the present disclosure;

FIG. 10 illustrates a schematic view of an example embodiment of a roll controlling arrangement according to the present disclosure;

FIG. 11 illustrates a block diagram of an example embodiment of a method and apparatus for controlling registration according to the present disclosure.

Detailed Description

Generally, the invention of the present disclosure is a system and method for producing two-sided microreplicated structures with side-to-side registration of better than about 100 microns, and preferably better than 50 microns, and more preferably less than 25 microns, and most preferably less than 5 microns. The system generally includes a first patterning assembly and a second patterning assembly. Each respective assembly creates a microreplicated pattern on a respective surface of a web having a first and a second surface. A first pattern is created on the first side of the web and a second pattern is created on the second surface of the web.

Each patterning assembly includes means for applying a coating, a patterning member, and a curing member. Typically, patterning assemblies include patterned rolls and a support structure for holding and driving each roll. Coating means of the first patterning assembly dispenses a first curable coating material on a first surface of the web. Coating means of the second patterning assembly dispenses a second curable coating material on a second surface of the web, wherein the second surface is opposite the first surface. Typically, first and second coating materials are of the same composition.

After the first coating material is placed on the web, the web passes over a first patterned member, wherein a pattern is created in the first coating material. The first coating material is then cured or cooled to form the first pattern. Subsequently, after the second

coating material is placed on the web, the web passes over a second patterned member, wherein a pattern is created in the second coating material. The second coating material is then cured to form the second pattern. Typically, each patterned member is a microreplicated tool and each tool typically has a dedicated curing member for curing the material. However, it is possible to have a single curing member that cures both first and second patterned materials. Also, it is possible to place the coatings on the patterned tools.

The system also includes means for rotating the first and second patterned rolls such that their patterns are transferred to opposite sides of the web while it is in continuous motion, and said patterns are maintained in continuous registration on said opposite sides of the web to better than about 100 microns.

An advantage of the present invention is that a web having a microreplicated structure on each opposing surface of the web can be manufactured by having the microreplicated structure on each side of the web continuously formed while keeping the microreplicated structures on the opposing sides registered generally to within 100 microns of each other, and typically within 50 microns, and more typically within 20 microns, and most typically within 5 microns.

Referring now to **FIGS. 1-2**, an example embodiment of a system **110** including casting apparatus **120** according to the present disclosure is illustrated. In the depicted casting apparatus **120**, a web **122** is provided to the casting apparatus **120** from a main unwind spool (not shown). The exact nature of web **122** can vary widely, depending on the product being produced. However, when the casting apparatus **120** is used for the fabrication of optical articles it is usually convenient for the web **122** to be translucent or transparent, to allow curing through the web **122**. The web **122** is directed around various rollers **126** into the casting apparatus **120**.

Accurate tension control of the web **122** is required to achieve the best results the invention is capable of, so the web **122** is directed over a tension-sensing device (not shown). In situations where it is desirable to use a liner web to protect the web **122**, the liner web is typically separated at the unwind spool and directed onto a liner web wind-up spool (not shown). The web **122** is typically directed via an idler roll to a dancer roller for precision

tension control. Idler rollers direct the web **122** to a position between nip roller **154** and first coating head **156**.

In the depicted embodiment, first coating head **156** is a die coating head. However, other coating methods can be adapted to the apparatus, as one of ordinary skill in the art will appreciate. The web **122** then passes between the nip roll **154** and first patterned roll **160**. The first patterned roll **160** has a patterned surface **162**, and when the web **122** passes between the nip roller **154** and the first patterned roll **160** the material dispensed onto the web **122** by the first coating head **156** is shaped into a negative of patterned surface **162**.

While the web **122** is in contact with the first patterned roll **160**, material is dispensed from second coating head **164** onto the other surface of web **122**. In parallel with the discussion above with respect to the first coating head **156**, the second coating head **164** is also a die coating arrangement including a second extruder (not shown) and a second coating die (not shown). In some embodiments, the material dispensed by the first coating head **156** is a composition including a polymer precursor and intended to be cured to solid polymer with the application of ultraviolet radiation.

Material that has been dispensed onto web **122** by the second coating head **164** is then brought into contact with second patterned roll **174** with a second patterned surface **176**. In parallel with the discussion above, in some embodiments, the material dispensed by the second coating head **164** is a composition including a polymer precursor and intended to be cured to solid polymer with the application of ultraviolet radiation.

At this point, the web **122** has had a pattern applied to both sides. A peel roll **182** may be present to assist in removal of the web **122** from second patterned roll **174**. Typically, web tension into and out of the casting apparatus is nearly constant.

The web **122** having a two-sided microreplicated pattern is then directed to a wind-up spool (not shown) via various idler rolls. If an interleave film is desired to protect web **122**, it is typically provided from a secondary unwind spool (not shown) and the web and interleave film are wound together on the wind-up spool at an appropriate tension.

Referring to **FIGS. 1-3**, first and second patterned rolls are coupled to first and second motor assemblies **210, 220**, respectively. Support for the motor assemblies **210, 220** is

accomplished by mounting assemblies to a frame **230**, either directly or indirectly. The motor assemblies **210, 220** are coupled to the frame using precision mounting arrangements. In the example embodiment shown, first motor assembly **210** is fixedly mounted to frame **230**. Second motor assembly **220**, which is placed into position when web **122** is threaded through the casting apparatus **120**, needs to be positioned repeatedly and is therefore movable, both in the cross- and machine direction. Movable motor arrangement **220** is preferably coupled to linear slides **222** to assist in repeated accurate positioning, for example, when switching between patterns on the rolls. Second motor arrangement **220** also includes a second mounting arrangement **225** on the backside of the frame **230** for positioning the second patterned roll **174** side-to-side relative to the first patterned roll **160**. Second mounting arrangement **225** preferably includes linear slides **223** allowing accurate positioning in the cross machine directions.

Referring to **FIG. 6**, a motor mounting arrangement is illustrated. A motor **633** for driving a tool or patterned roll **662** is mounted to the machine frame **650** and connected through a coupling **640** to a rotating shaft **601** of the patterned roller **662**. The motor **633** is coupled to a primary encoder **630**. A secondary encoder **651** is coupled to the tool to provide precise angular registration control of the patterned roll **662**. Primary **630** and secondary **651** encoders cooperate to provide control of the patterned roll **662** to keep it in registration with a second patterned roll, as will be described further hereinafter.

In the example embodiment shown, the tool roller **662** diameter is typically smaller than its motor **633** diameter. To accommodate this arrangement, the two tool roller assemblies **610, 710** are installed as mirror images in order to be able to bring the two tool rollers **662, 762** together as shown in **FIG. 7**. Referring also to **FIG.1**, the first motor arrangement is typically fixedly attached to the frame and the second motor arrangement is positioned using movable optical quality linear slides.

Reduction or elimination of shaft resonance is important as this is a source of registration error allowing pattern position control within the specified limits. Using a coupling **640** between the motor **633** and shaft **650** that is larger than general sizing schedules specify will also reduce shaft resonance caused by more flexible couplings. Bearing

assemblies **660** are located in various locations to provide rotational support for the motor arrangement.

Referring to **FIG. 4**, an example embodiment of a casting apparatus **420** for producing a two-sided web **422** with registered microreplicated structures on opposing surfaces is illustrated. Assembly includes first and second coating means **456, 464**, a nip roller **454**, and first and second patterned rolls **460, 474**. Web **422** is presented to the first coating means **456**, in this example a first extrusion die **456**. First die **456** dispenses a first curable liquid layer coating **470** onto the web **422**. First coating **470** is pressed into the first patterned roller **460** by means of a nip roller **454**, typically a rubber covered roller. While on the first patterned roll **460**, the coating is cured using an external curing source **480**, for example, a lamp, of suitable wavelength light, typically an ultraviolet light.

A second curable liquid layer **481** is coated on the opposite side of the web **422** using a second side extrusion die **464**. The second layer **481** is pressed into the second patterned tool roller **474** and the curing process repeated for the second coating layer **481**. Registration of the two coating patterns is achieved by maintaining the tool rollers **460, 474** in a precise angular relationship with one another, as will be described hereinafter.

Referring to **FIG. 5**, a close-up view of a portion of first and second patterned rolls **560, 574** is illustrated. First patterned roll **560** has a first pattern **562** for forming a microreplicated surface. Second pattern roll **574** has a second microreplicated pattern **576**.

In the example embodiment shown, first and second patterns **562, 576** are the same pattern, though the patterns may be different. As a web **522** passes over the first roll **560**, a first curable liquid (not shown) on a first surface **524** is cured by a curing light source **525** near a first region **526** on the first patterned roll **560**. A first microreplicated patterned structure **590** is formed on the first side **524** of the web **522** after the liquid is cured. The first patterned structure **590** is a negative of the pattern **562** on the first patterned roll **560**. After the first patterned structure **590** is formed, a second curable liquid **581** is dispensed onto a second surface **527** of the web **522**. To insure that the second liquid **581** is not cured prematurely, the second liquid **581** is isolated from the first curing light **525**, typically by a locating the first curing light **525** so that it does not fall on the second liquid **581**.

Alternatively, shielding means **592** can be placed between the first curing light **525** and the second liquid **581**. Also, the curing sources can be located inside their respective patterned rolls where it is impractical or difficult to cure through the web.

After the first patterned structure **590** is formed, the web **522** continues along the first roll **560** until it enters the gap region **575** between the first and second patterned rolls **560, 574**. The second liquid **581** then engages the second pattern **576** on the second patterned roll and is shaped into a second microreplicated structure, which is then cured by a second curing light **535**. As the web **522** passes into the gap **575** between first and second patterned rolls **560, 574**, the first patterned structured **590**, which is by this time substantially cured and bonded to the web **522**, restrains the web **522** from slipping while the web **522** begins moving into the gap **575** and around the second patterned roller **574**. This removes web stretching and slippages as a source of registration error between the first and second patterned structures formed on the web.

By supporting the web **522** on the first patterned roll **560** while the second liquid **581** comes into contact with the second patterned roll **574**, the degree of registration between the first and second microreplicated structures **590, 593** formed on opposite sides **524, 527** of the web **522** becomes a function of controlling the positional relationship between the surfaces of the first and second patterned rolls **560, 574**. The S-wrap of the web around the first and second patterned rolls **560, 574** and between the gap **575** formed by the rolls minimizes effects of tension, web strain changes, temperature, microslip caused by mechanics of nipping a web, and lateral position control. Typically, the S-wrap maintains the web **522** in contact with each roll over a wrap angle of 180 degrees, though the wrap angle can be more or less depending on the particular requirements.

To increase the degree of registration between the patterns formed on opposite surfaces of a web, it preferred to have a low-frequency pitch variation around the mean diameter of each roll. Typically, the patterned rolls are of the same mean diameter, though this is not required. It is within the skill and knowledge of one having ordinary skill in the art to select the proper roll for any particular application.

Example #1

Because the features sizes on the microreplicated structures on both surfaces of a web are desired to be within fine registration of one another, the patterned rolls need to be controlled with a high degree of precision. Cross-web registration within the limits described herein can be accomplished by applying the techniques used in controlling machine-direction registration, as described hereinafter. Control of registration in the machine direction is required, which heretofore has not been achieved in two-sided microreplicated webs. For example, to achieve about 10 microns end-to-end feature placement on a 10-inch circumference patterned roller, each roller must be maintained within a rotational accuracy of ± 32 arc-seconds per revolution. Control of registration becomes more difficult as the speed the web travels through the system is increased.

Applicants have built and demonstrated a system having 10-inch circular patterned rolls that can create a web having patterned features on opposite surfaces of the web that are registered to within 2.5 microns. Upon reading this disclosure and applying the principles taught herein, one of ordinary skill in the art will appreciate how to accomplish the degree of registration for other microreplicated surfaces.

Referring to **FIG. 8**, a schematic of a motor arrangement **800** used in Applicants' system is illustrated. Motor arrangement includes a motor **810** including a primary encoder **830** and a drive shaft **820**. Drive shaft **820** is coupled to a driven shaft **840** of patterned roll **860** through a coupling **825**. A secondary, or load, encoder **850** is coupled to the driven shaft **840**. Using two encoders in the motor arrangement described allows the position of the patterned roll to be measured more accurately by locating the measuring device (encoder) **850** near the patterned roll **860**, thus reducing or eliminating effects of torque disturbances when the motor arrangement **800** is operating.

Referring to **FIG. 9**, a schematic of the motor arrangement of **FIG. 8**, is illustrated as attached to control components. In the example apparatus shown in **FIGS. 1-3**, a similar set-up would control each motor arrangement **210** and **220**.

Motor arrangement **900** communicates with a control arrangement **965** to allow precision control of the patterned roll **960**. Control arrangement **965** includes a drive module

966 and a program module **975**. The program module **975** communicates with the drive module **966** via a line **977**, for example, a SERCOS fiber network. The program module **975** is used to input parameters, such as set points, to the drive module **966**. Drive module **966** receives input 480 volt, 3-phase power **915,** rectifies it to DC, and distributes it via a power connection **973** to control the motor **910**. Motor encoder **912** feeds a position signal to control module **966**. The secondary encoder **950** on the patterned roll **960** also feeds a position signal back to the drive module **966** via to line **971**. The drive module **966** uses the encoder signals to precisely position the patterned roll **960**. The control design to achieve the degree of registration is described in detail below.

In the example embodiments shown, each patterned roll is controlled by a dedicated control arrangement. Dedicated control arrangements cooperate to control the registration between first and second patterned rolls. Each drive module communicates with and controls its respective motor assembly.

Various options are available for co-coordinating the two axes such as master/slave-type and parallel configurations, which was used in Applicants' system.

The control arrangement in the system built and demonstrated by Applicants include the following. To drive each of the patterned rolls, a high performance, low cogging torque motor with a high-resolution sine encoder feedback (512 sine cycles x 4096 drive interpolation >> 2 million parts per revolution) was used, model MHD090B-035-NG0-UN, available from Bosch-Rexroth (Indramat). Also the system included synchronous motors, model MHD090B-035-NG0-UN, available from Bosch-Rexroth (Indramat), but other types, such as induction motors could also be used. Each motor was directly coupled (without gearbox or mechanical reduction) through an extremely stiff bellows coupling, model BK5-300, available from R/W Corporation. Alternate coupling designs could be used, but bellows style generally combines stiffness while providing high rotational accuracy. Each coupling was sized so that a substantially larger coupling was selected than what the typical manufacturers specifications would recommend. Additionally, zero backlash collets or compressive style locking hubs between coupling and shafts are preferred. Each roller shaft was attached to an encoder through a hollow shaft load side encoder, model RON255C,

available from Heidenhain Corp., Schaumburg, IL. Encoder selection should have the highest accuracy and resolution possible, typically greater than 32 arc-sec accuracy. Applicants' design, 18000 sine cycles per revolution were employed, which in conjunction with the 4096 bit resolution drive interpolation resulted in excess of 50 million parts per revolution resolution giving a resolution substantially higher than accuracy. The load side encoder had an accuracy of +/- 2 arc-sec; maximum deviation in the delivered units was less than +/- 1 arc-sec.

Preferably, each shaft is designed to be as large a diameter as possible and as short as possible to maximize stiffness, resulting in the highest possible resonant frequency. Precision alignment of all rotational components is desired to ensure minimum registration error due to this source of registration error. One of ordinary skill in the art will recognize that there are various ways to reduce registration error due to alignment of the rotational components.

The control strategy for each axis is implemented as follows:

Referring to **FIG. 11,** in Applicants' system identical position reference commands were presented to each axis simultaneously through a SERCOS fiber network at a 2 ms update rate. Each axis interpolates the position reference with a cubic spline, at the position loop update rate of 250 microsecond intervals. The interpolation method is not critical, as the constant velocity results in a simple constant times time interval path. The resolution is critical to eliminate any round off or numerical representation errors. Axis rollover must also be addressed. It is critical that each axis' control cycle is synchronized at the current loop execution rate (62 microsecond intervals).

The top path **1151** is the feed forward section of control. The control strategy includes a position loop **1110**, a velocity loop **1120**, and a current loop **1130**. The position reference **1111** is differentiated, once to generate the velocity feed forward terms **1152** and a second time to generate the acceleration feed forward term **1155**. The feed forward path **1151** helps performance during line speed changes and dynamic correction.

The position command **1111** is subtracted from current position **1114**, generating an error signal **1116**. The error **1116** is applied to a proportional controller **1115**, generating the velocity command reference **1117**. The velocity feedback **1167** is subtracted from the

command **1117** to generate the velocity error signal **1123**, which is then applied to a PID controller. The velocity feedback **1167** is generated by differentiating the motor encoder position signal **1126**. Due to differentiation and numerical resolution limits, a low pass Butterworth filter **1124** is applied to remove high frequency noise components from the error signal **1123**. A narrow stop band (notch) filter **1129** is applied at the center of the motor – roller resonant frequency. This allows substantially higher gains to be applied to the velocity controller **1120**. Increased resolution of the motor encoder also would improve performance. The exact location of the filters in the control diagram is not critical; either the forward or reverse path are acceptable, although tuning parameters are dependent on the location.

A PID controller could also be used in the position loop, but the additional phase lag of the integrator makes stabilization more difficult. The current loop is a traditional PI controller; gains are established by the motor parameters. The highest bandwidth current loop possible will allow optimum performance. Also, minimum torque ripple is desired.

Minimization of external disturbances is important to obtaining maximum registration. This includes motor construction and current loop commutation as previously discussed, but minimizing mechanical disturbances is also important. Examples include extremely smooth tension control in entering and exiting web span, uniform bearing and seal drag, minimizing tension upsets from web peel off from the roller, uniform rubber nip roller. In the current design a third axis geared to the tool rolls is provided as a pull roll to assist in removing the cured structure from the tool.

The web material can be any suitable material on which a microreplicated patterned structure can be created. Examples of web materials are polyethylene terephthalate, polymethyl methacrylate, or polycarbonate. The web can also be multi-layered. Since the liquid is typically cured by a curing source on the side opposite that on which the patterned structure is created, the web material must be at least partially translucent to the curing source used. Examples of curing energy sources are infrared radiation, ultraviolet radiation, visible light radiation, microwave, or e-beam. One of ordinary skill in the art will appreciate that other curing sources can be used, and selection of a particular web material/curing source

combination will depend on the particular article (having microreplicated structures in registration) to be created.

An alternative to curing the liquid through the web would be to use a two part reactive cure, for example, an epoxy, which would be useful for webs that are difficult to cure through, such as metal web or webs having a metallic layer. Curing could be accomplished by in-line mixing of components or spraying catalyst on a portion of the patterned roll, which would cure the liquid to form the microreplicated structure when the coating and catalyst come into contact.

The liquid from which the microreplicated structures are created is typically a curable photopolymerizable material, such as acrylates curable by UV light. One of ordinary skill in the art will appreciate that other coating materials can be used, for example, polymerizable material, and selection of a material will depend on the particular characteristics desired for the microreplicated structures. Similarly, the particular curing method employed is within the skill and knowledge of one of ordinary skill in the art. Examples of curing methods are reactive curing, thermal curing, or radiation curing.

Examples of coating means that useful for delivering and controlling liquid to the web are, for example, die or knife coating, coupled with any suitable pump such as a syringe or peristaltic pump. One of ordinary skill in the art will appreciate that other coating means can be used, and selection of a particular means will depend on the particular characteristics of the liquid to be delivered to the web.

Various modifications and alterations of the present invention will be apparent to those skilled in the art without departing from the scope and spirit of this invention, and it should be understood that this invention is not limited to the illustrative embodiments set forth herein.